The Ozone Hole of 2002 as Measured by TOMS

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ABSTRACT

Since its discovery in 1985, the ozone hole has been regularly mapped using the data from Total Ozone Mapping Spectrometer (TOMS) instruments on several satellites. The current TOMS, on the Earth Probe satellite, has been taking measurements since 1996. The ozone hole first appeared during the 1980s. Since 1990, the hole has consistently developed during each Antarctic spring over a broad area with the minimum total ozone value reaching about 100 Dobson units (DU; 1 DU = 2.69×10^{16} molecules cm^{-2}) in late September or early October. The year 2002 was markedly different from the past 12 years. A series of strong wave events weakened the South Polar vortex. In late September, a major stratospheric warming took place, reversing the direction of the polar flow and the latitudinal temperature gradient. This warming resulted in a division of the ozone hole into two pieces, one that migrated to lower latitudes and disappeared and one that reformed over the Pole in a weakened form. The development of this year's unusual ozone hole is shown here and is contrasted to a climatology of the years since 1990. Minimum daily values of total ozone barely reached 150 DU in contrast to values nearer to 100. The area of the ozone hole briefly reached 18×10^6 km^2, then dropped rapidly to only 2×10^6 km^2, and finally recovered to about 8×10^6 km^2 before disappearing in early November. The positive anomaly compared with the last 12 yr near the Pole was accompanied by a smaller negative anomaly north of 45°S.

1. Introduction

The ozone hole was discovered by Farman et al. (1985) from the analysis of their ground-based Dobson spectrophotometer measurements at the Halley Bay Station. Shortly thereafter, the aerial extent of the hole was mapped using Total Ozone Mapping Spectrometer (TOMS) and Solar Backscatter UV (SBUV) data from the *Nimbus-7* satellite (Stolarski et al. 1986). The development of the ozone hole was followed in subsequent years from satellite measurements (e.g., Krueger et al. 1988, 1989, Stolarski et al. 1990, Newman et al. 1991, McCormick and Larsen 1988, Herman et al. 1995a,b; Bevilacqua et al. 1995, 1997) and from ground-based and balloon measurements (e.g., Hofmann et al. 1987; Komhyr et al. 1989). Since about 1990, the ozone hole has followed a similar course during each year. A rapid decrease in total ozone occurs from late August until late September. A minimum is reached in late September or early October. The minimum occurs when the ozone concentration between about 14 and 22 km approaches zero concentration (Hofmann et al. 1997).

The ozone hole has continued to be mapped by a series of TOMS instruments. The original *Nimbus-7* TOMS provided mapping of the Antarctic from its launch in 1978 until it finally failed in May of 1993. Mapping of the ozone hole for 1993 and 1994 was done by the TOMS instrument on the *Meteor-3* satellite, but the rapidly precessing orbit of *Meteor-3* led to some gaps in the coverage during those years. In July of 1996, the Earth Probe TOMS was launched. This instrument has now mapped the ozone hole each year from 1996 through 2002. Beginning in late 2000, there have been calibration problems with the Earth Probe (EP) TOMS instrument. These appear to be related to degradation of the mirror that scans the field of view (FOV) left and right across the orbit track to provide full mapping. Corrections have been applied to remove the primary effect, a scan-angle dependence. Fortunately, the scan-angle dependence is only a minor problem at high latitudes, where the high scan-angle FOVs are not needed because of convergence of the orbit tracks. A second effect is added uncertainty in the absolute calibration. By 2002, this uncertainty is 3%–5%. This represents a significant error for ozone trend determination, but for our purpose of comparing the 2002 ozone hole to previous years, this calibration uncertainty is small. As seen below, the differences of interest are tens of percent.

The unusual meteorology of 2002 has been described in more detail by Newman and Nash (2005). A se-

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quence of wave events weakened the vortex and seems to have dynamically "preconditioned" the vortex for the major warming that began on 22 September. The wave events and disturbance of the vortex affects the total ozone column amount in two ways. First, the wave disturbances decelerate the mean flow leading to a stronger overturning circulation with increased descent in the polar region. This descent brings down air with higher mixing ratios of ozone, thus increasing the column (air flowing into the polar region at high altitudes has a higher mixing ratio of ozone than air flowing out of the polar region at lower altitudes). Second, the increased descent warms the air, thus suppressing the formation of polar stratospheric clouds and the potential denitrification of the air. Although 2002 was unique in that a major warming occurred with zonal-mean wind reversal, there have previously been warm winters showing an unusually warm and disturbed polar vortex. In particular, 1986 and 1988 had warm Antarctic stratospheric temperatures during the spring. In between these years, 1987 had a strong vortex with cold temperatures and a strong, long-lasting ozone hole.

Since the alternating warm and cold stratospheric winters of 1986, we have had a string of relatively consistent Antarctic conditions. The Antarctic ozone minimum has reached relatively small total column amounts with stable, long-lasting vortices. For the purpose of illustrating the unusual nature of the 2002 ozone hole, we will compare the ozone measurements from EP TOMS with a climatology developed from the years since 1990. For that climatology, we have put together the measurements for 8 yr in which we have TOMS coverage over the entire ozone hole season. These 8 yr consist of 3 yr of *Nimbus-7* TOMS measurements (1990–92) and 5 yr of EP TOMS measurements (1997–2001).

2. 2002 ozone hole as measured by TOMS

Figure 1 shows maps made from the ozone measurements of EP TOMS for four days during September and October of 2002. The days chosen are separated by 5 days starting on 18 September. By 23 September, the ozone hole actually split into two pieces (top right) that drifted off the Pole toward lower latitudes (bottom left). The remnant of the ozone hole fragment near the tip of South America drifted farther to the north and dissipated. The remnant south of the African continent drifted back toward the Pole and reformed a significantly weakened ozone hole (bottom right).

a. Minimum and area

To understand the unique nature of the ozone hole for 2002, we compare it to the climatology of measurements made by the TOMS instruments for 1990–92 and 1997–2001. One of the common measures of the state of the ozone hole has been the daily minimum value measured by TOMS. Figure 2 shows this daily minimum for 2002 plotted as dots, compared to the 1990–2001 climatology. The mean climatology is shown as a heavy white line inside a shaded area that represents the extremes that occurred during the years of the climatology. This presentation of the minimum is similar to others, except that we form the climatology only from the recent years with deep, long-lasting ozone holes. If we had used the 25-yr climatology, the shaded area would extend upward to significantly higher total ozone values representing earlier years, especially 1979, when the ozone hole was only beginning to form. The presentation in Fig. 2 clearly shows that the 2002 ozone hole was out-

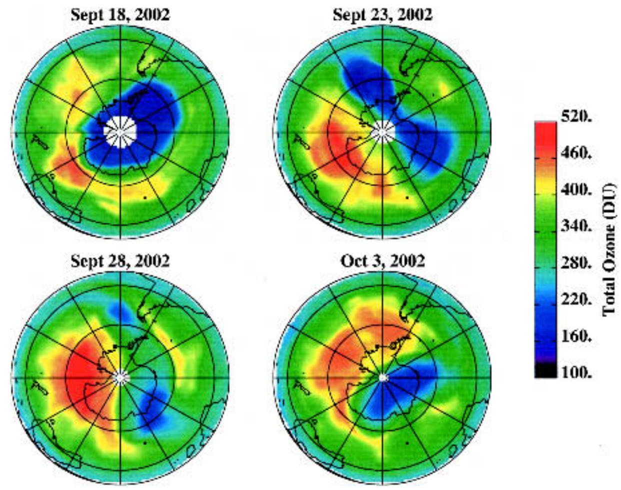

FIG. 1. TOMS total ozone maps for four days during Sep and Oct 2002. White space around the South Pole is polar night where no measurements are made.

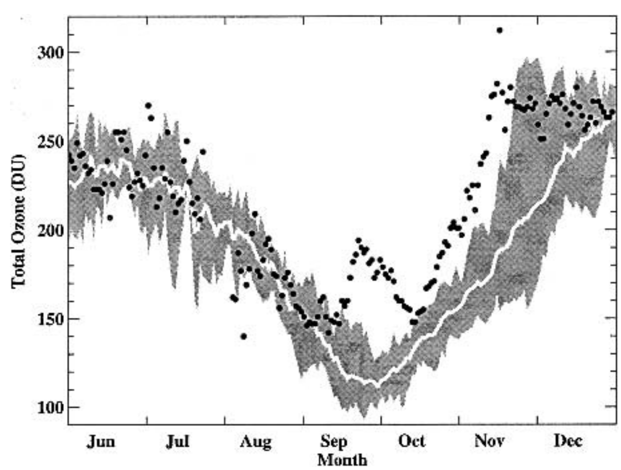

FIG. 2. Daily minimum total ozone measured by TOMS between 40° and 90°S. Black dots indicate data for 2002. Shaded area indicates range for 8 yr during the period 1990–2001. The 8 yr with available TOMS data are 1990–92 and 1997–2001. The white line through the middle of the shaded area is the mean for the 8 yr.

side the range of what occurred for the previous decade.

Note particularly in Fig. 2 that the minimum total ozone measurement went outside the climatological range in mid-September as the major warming was occurring and the vortex was dividing into two pieces. The peak of the minimum ozone was reached in late September at a little more than 190 Dobson units (DU; 1 DU = 2.69×10^{16} molecules cm^{-2}). The total ozone minimum then declined as the vortex reformed about the single remnant. This decline continued into the second week of October when a minimum of about 150 DU was reached. This value was at the upper limit of the climatology for that time of year. The vortex then weakened again and began its final breakup. Note that the recovery as measured by the minimum total ozone occurred significantly more rapidly than the climatological mean recovery. The minimum total ozone amounts were several tens of Dobson units above the upper envelope of the climatology. The vortex breakup, as seen in the ozone minimum, was complete by the second week in November, significantly earlier than any of the last 12 yr.

Another good measure of the progress of the ozone hole over the course of a season is the plot of area shown in Fig. 3. The area is defined as the region where the total ozone as measured by TOMS is less than 220 DU. The value 220 DU was chosen to define the ozone hole because it is almost always a middle value in a strong spatial gradient of total ozone. Again, 2002 is shown in the figure by dots, while the mean climatology is represented by the thick white line, and the range of the climatology is indicated by the shaded area. The growth of the area of the ozone hole for 2002 lags significantly behind the climatological years even before the final warming event. A sequence of wave events, as described by Newman and Nash (2005) weakened the vortex and transported more ozone into the vortex on the overturning circulation than in any of the years represented in the climatology.

By the second week in September, the 2002 ozone hole had developed as in previous recent years, except that it was smaller. When the major warming occurred, the area where measurements were less than 220 DU plummeted to only about 10%, or 2×10^6 km^2, of the normal area for that time. This minimum coincides with the time when the vortex split into two pieces. As the vortex remnant south of Africa moved back toward the Pole, it strengthened, and the area of the ozone hole, as defined by 220 DU, increased to about 8×10^6 km^2, peaking in mid-October. The area decreased to zero in early November and remained there for the rest of the season. This was the earliest disappearance of the ozone hole in more than a decade by more than a month.

b. *Mapped comparison to 1990–2001 climatology*

One of the standard measures adopted for the ozone hole has been the value for total column ozone averaged over the month of October (see, e.g., Farman et al. 1985). Figure 4 maps the monthly mean total ozone amount over the Antarctic. The monthly mean climatology for the 8 yr illustrates what has become the typical ozone hole. The climatological ozone hole has a deep minimum of about 140 DU, pushed slightly off the Pole along the prime meridian. This region of low ozone is surrounded by a crescent-shaped maximum, also pushed off the center of the Pole with a strong wave 1 with amplitude of nearly 80 DU. The maximum of this wave-1 amplitude is located just south of Aus-

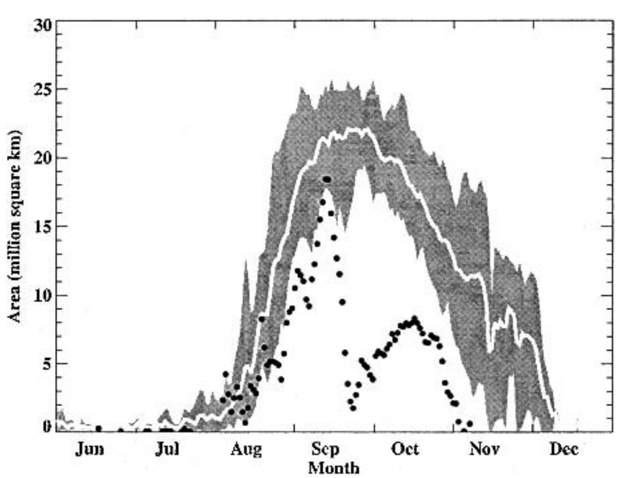

FIG. 3. Same as in Fig. 2, but for daily area where total ozone measured by TOMS is less than 220 DU.

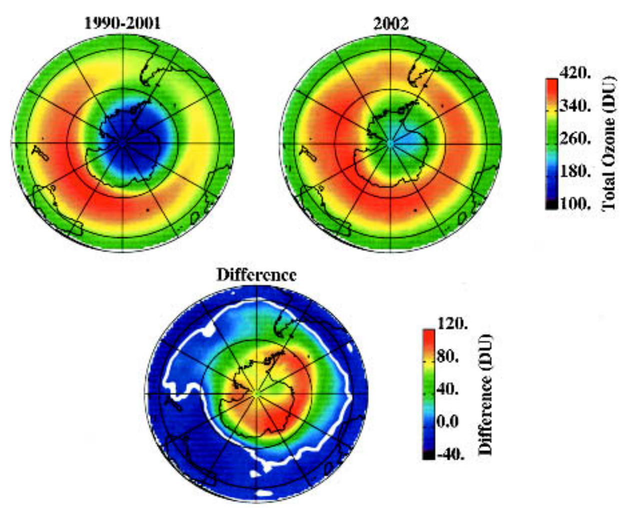

FIG. 4. (top left) The monthly average climatology for Oct, compiled from 8 yr (1990–92 and 1997–2001). (top right) The 2002 Oct monthly average. (bottom) The monthly average difference between Oct 2002 and the 8-yr ozone hole climatology. The thick white contour indicates the zero line for the difference between 2002 and the climatology. All maps are orthographic projections with the South Pole at the center.

tralia at about 55°S latitude. The October mean for 2002 displays many of the same features, including the displacement off the Pole and the crescent-shaped maximum. However, the 2002 ozone hole has a minimum October mean of 210 DU. It has a similar maximum to the crescent in the same general location as the climatology, but the wave-1 feature has an amplitude of only about 40 DU.

Figure 4 (bottom) shows the difference between the October mean ozone hole for 2002 and the climatology for 1990–2001 in DU. The difference is positive over a significant fraction of the hemisphere and strongly positive (> 60 DU) over a region somewhat larger than the ozone hole itself. The difference becomes negative at a latitude that ranges from 30° to 60°S. The average difference between 2002 and the climatology since 1990 averaged over the entire Southern Hemisphere is 7.5 DU, or about 2.5%. The pattern of difference is consistent with an increase in the residual overturning circulation discussed by Newman and Nash (2005). This increase in the residual circulation leads to a decrease in tropical ozone concurrent with an increase in mid- to high-latitude ozone. The overall hemispheric decrease is also consistent with the secondary effect of the warmer vortex and reduced heterogeneous conversion of reservoir chlorine (HCl and $ClONO_2$) to active ClO. This leads to a lessening of the catalytic destruction of ozone during the spring season compared to a more typical year with weak wave disturbance and strong polar vortex.

The development of the pattern of difference between 2002 and the 1990–2001 climatology is shown in Fig. 5. The pattern where the measurements for 2002 are lower than the climatology at low latitudes and higher than the climatology at higher latitudes begins to

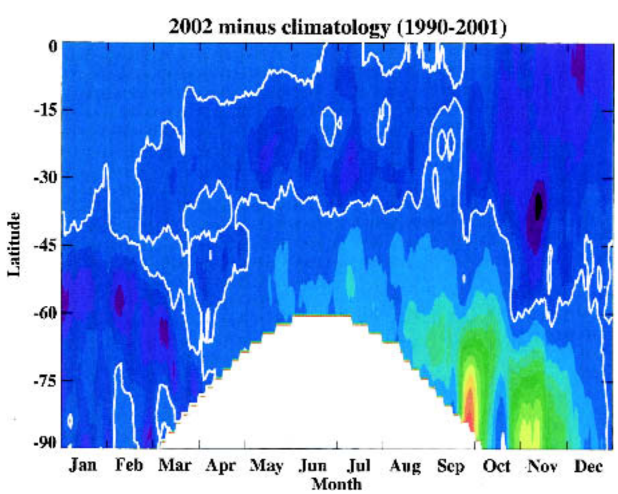

FIG. 5. The daily zonal-mean difference between 2002 and the 8-yr ozone hole climatology as a function of time and latitude. The heavy white line indicates zero. Dark blues to purple are negative (i.e., 2002 has less ozone than the 8-yr climatology). Lighter blues up to red are positive anomalies.

set up in the early winter. By mid-June, the pattern is well established with ozone for 2002 being below climatology at latitudes between the equator and 45°S and above climatology from 45°S to the polar night boundary (and presumably to the Pole).

In mid-September, when the major warming occurs, the pattern strengthens. The low-latitude decrease from climatology becomes more firmly established. The high-latitude total ozone rapidly becomes much higher than climatology at latitudes south of 75°S as indicated by the yellow-to-red colors in Fig. 5. This is the region and time period for the major ozone decrease caused by chlorine in the ozone hole. The observations are consistent with the warm temperatures of 2002 that suppress the normal chemical mechanism of ozone hole formation. This is another way of seeing that the ozone hole did not get as deep or as large during its prime formation season.

In November, Fig. 5 indicates that, again, the 2002 measurements south of 75°S rapidly increase over the climatology. This is the time period when ozone hole recovery begins in 2002 a month earlier than in any of the years in the climatology. Thus, the second yellow region in the figure is a result of increases in 2002, while the first was a result of decreases in the climatology years.

3. Summary

The TOMS instruments have been measuring the development of the ozone hole for most of the years from 1979 to the present. These measurements have clearly shown the patterns of development of this phenomenon over the Antarctic region and the entire Southern Hemisphere. The development of the ozone hole reached a relatively stable point by 1990 when virtually all of the ozone was removed over a range of altitudes each year. This highly developed ozone hole then formed each year in a new "normal" Antarctic ozone pattern that was stable from year to year. The climatology of the development and persistence of the ozone hole remained within quite narrow bounds during the 1990s compared to the development years of the hole during the 1980s, despite the eruption of Pinatubo in 1992.

The pattern was broken in 2002 with a very unusual dynamical year. Wave events weakened the vortex, warmed its air, and reduced the potential for ozone destruction. The major warming in September split the vortex into two distinct pieces. The area of the ozone hole as defined by the 220-DU contour, was reduced to about 2×10^6 km^2. The subsequent reformation of the vortex from one of the split remnants remained weak and was broken up in November, about a month earlier than any recent ozone hole.

The development of the 2002 ozone hole throughout the season was different from the recent climatology because of the unusual dynamics occurring in the stratosphere. The pattern of the development is consistent with what we understand about the chemistry and dynamics of the ozone hole. The observations do not indicate any need, at this time, to revise our understanding of the interaction of dynamics and chemistry to form the ozone hole. The 2002 Antarctic winter and spring do remind us that the atmosphere's variability is large and can lead to significant, unpredictable interannual variability. The unusual nature of the 2002 ozone hole is caused by dynamics, as far as is known, and has no direct implications for ozone recovery.

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